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Laser Countermeasure Impacts and Penalties

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LASER COUNTERMEASURE IMPACTS AND PENALTIES

by

Gregory H. Canavan

ABSTRACT

Countermeasures could determine the ultimate effectiveness of directed energy weapons. This report discusses shielding and spinning boosters, the countermeasures specific to lasers, and provides an overall assessment of their impact, which is modest.

I. INTRODUCTION

Countermeasures could determine the ultimate effectiveness of directed energy weapon (DEW) concepts. Whether lasers, mirrors, and particle beams could be built has been questioned less than whether it would be cheaper to deploy or to countermeasure them. Generic countermeasures such as fast burn boosters, fast buses, and compact launch areas are discussed elsewhere. They impact all DEW concepts similarly, extracting significant but acceptable penalties from each concept.[1] This report gives a detailed discussion of shielding and spinning the boosters, which are the countermeasures specific to lasers, and provides an overall assessment of their impact.

II. CONSTELLATION SCALING WITH HARDENING

Current missiles are not intentionally shielded against DEWs, so fluences of a few kJ/cm^2 could be lethal to them. Current boosters also require long deployment times, so their launches could be met by constellations of a few tens of 5 MW lasers with 4 m mirrors, or "5-4" chemical laser platforms.[2] That, however, would not provide the margin desired against future harder, faster, and more compact missiles, buses, and launch areas. Thus, "nominal" calculations have actually used the highest level of hardening thought to be ultimately attainable.[3] That level of hardening, engagement time, and basing requires about 50 lasers of the 20-10 level of performance in correct scaling estimates.[4]

Limiting calculations with arbitrarily high hardnesses distort, however, the impact of DEWs because these calculations fail to take into account the offensive penalties involved in attaining them. The main laser countermeasures are hardening or spinning the missiles. Since hardening primarily involves adding mass, it is sometimes stated that any desired hardening could be attained by adding more mass. That is not, however, the case for missiles that must deliver useful payloads to intercontinental ranges. For them, any hardening mass reduces the payload, quite significantly in general. The penalties associated with such hardening are discussed below.

III. HARDENING ANALYSES

Hardening is achieved by adding ablative materials to the missile's exterior to protect its soft internal elements from laser radiation. Practical schemes must add the material over the whole booster, whose area can be several thousand times greater than the spot irradiated by the laser. That leads to a competition between the laser's preferential attack and the roughly 100-fold higher efficiency of ablation of the hardening material. The net effect can favor the laser by a factor of

2 to 10. The paragraphs below review recent treatments of hardening; the following section assesses the impact of spinning boosters.

A. Recent Estimates of Hardening Penalties

There have been several recent discussions of hardening. This section reviews their key features, which are largely common.

1. Office of Technology Assessment (OTA)

Two reports by the OTA discussed missile hardening in the boost phase. The first assumed, without justification, that hardening could attain arbitrarily large levels and inflict linearly growing penalties in the defense with no penalty in the performance or payload of the missile.[5] The second report simply postulated that different levels of hardening could be achieved and evaluated the impact they would have on the laser constellations required, but not on the offensive missiles themselves.[6] Neither report treats the penalties of greatest concern in practical situations.

2. Union of Concerned Scientists (UCS)

Like the OTA, the UCS assumed that boosters could be made very hard without significant payload penalty.[7] The UCS reports' emphasis was, however, primarily on the impact of spinning the boosters, rather than hardening them.

3. American Physical Society (APS)

In its study of DEWs, the APS examined the impact of hardening, presenting the equations for hardening a "nominal SS-18" and estimating the payload penalties for various hardenings. The retrofit hardening assumed did not, however, protect all stages of the missiles. The APS estimates effectively hardened only the first stages, for which the hardening penalty is least. The impact of correcting that approximation is shown below. Even with partial shielding, however, the APS calculation showed significant reductions in the missiles' payloads.

B. Hardening Calculations

The penalty for hardening depends on the type and configuration of the missile to be shielded. The APS report presents estimates for an optimally staged, unshielded SS-18s, which are used as the basis for the estimates below. The sensitivities of other types of missiles are discussed later.

For hardening by the retrofit addition of ablator, uniform hardening of all stages requires that material be added uniformly in proportion to the areas of the stages, so that the resulting hardening would be uniformly thick over all exposed components. The SS-18 is about 32 m high. The first stage is about 20 m long, the second 8 m, and the bus about 4 m. Since its diameter is constant at about 3 m, the areas are in the ratio 20:8:4 = 5:2:1, ignoring the additional hardening required for the 7 m^2 area of the top of the bus.[8] Uniform hardening would thus allocate hardening to the first and upper stages in the ratio of their areas, or about 1.7:1.

The APS report arbitrarily assumed that the shielding mass for the stages are proportional to their unshielded masses, which are quite dissimilar. The first and second stage masses were 146 and 30 tons, respectively, i.e., in a ratio of 4.8:1. Thus, in allocating its postulated 6 metric tons of hardening, the APS was lead to first and second stage hardening masses of 4.8 and 1 tons, respectively.[9]

The SS-18's stage masses are in the ratio 4.8:1, but their areas are in the ratio 1.7:1, so the APS's estimates were based on a retrofit, for which the first stage was be harder than the upper stages by about a factor of 4.8/1.7 = 2.9. That would leave the upper stages--the ones most subject to attack--relatively unhardened. Correcting the APS's mass allocation shifts hardening mass from the first stage up to the second stage and bus, producing a much larger impact on payload.

The modification of the equations for uniform hardening of all stages, which is straightforward, is given in Appendix A.[10]

Figure 1 shows the resulting payload mass as a function of hardening mass. The figure is constructed for the conditions of the APS report, which considered nominal hardening to be the retrofit addition of a total of 6 metric tons of of ablator. For that hardening, applied in proportion to stage mass, the payload reduction is about 1.8 tons, as shown in the top curve.

The lower curve on Fig. 1 is for uniform hardening of all stages. For the same total mass, but with more of it uniformly applied to the upper stages, uniform hardening would reduce the payload by about 3 tons. That is about double the APS's penalty, which is a direct measure of error of the APS's approximation.

C. Impact of Additional Hardening

The unshielded SS-18 post boost vehicle (PBV) has ten 300 kg reentry vehicles (RVs), 3 tons of fuel, and 2 tons of structure. Short of total bus redesign, every 300-600 kg reduction in payload reduces the number of RVs by one. The lower value, 300 kg, corresponds to the elimination of RVs only; the larger value, 600 kg, to the offloading of a corresponding amount of fuel with each RV, which would limit the missions possible with those remaining.[11] Advanced boosters can have buses that provide about 10% of the RVs' axial velocity. Current SS-18 are heavily cross targeted, which requires about the amount of fuel on board. Thus, if fuel was removed for hardening, their range and missions would be impacted directly. When fuel is offloaded along with the RVs, the APS report estimates a net reduction of 3 RVs; for RVs only, the reduction would be 6 RVs, which amount to 30 and 60%, respectively, of the total weapons carried on the SS-18.

For uniform hardening, the payload reduction is about 3 tons. That would require the removal of 5-10 RVs, i.e., 50-100% of the weapons, depending on the mission degradation accepted. The use of small, individual buses for each RV has been suggested as a counter to such boost phase defenses. The mass of such small individual buses could, however, approach that of the RV it carries, which would amount to a factor of 2 penalty

in payload, since the buses' mass must also be subtracted from the useful payload. If so, the scaling for launches with individual buses would be about the same as that for the current large buses for the case in which RVs and fuel were offloaded together.

D. Further Hardening

The payload penalty increases about linearly if more mass is required to achieve the needed hardening. If the ablator thickness was doubled, giving a total hardening mass of 12 tons, for uniform hardening, all the RVs and fuel would have to be removed from current buses. The remaining payload of about 2 tons could, however, presumably be reconfigured into about 2,000 kg ÷ 600 kg/RV = 3 RVs with individual buses. Even with that reconfiguration of the residual, that level of hardening would require about a 70% reduction of the threat.

The simple results used here are consistent with the results of more detailed calculations by others. Analyses by Martin Marietta differ little from the approximate calculation in Fig. 1. For 6 tons of uniform hardening, Fig. 1 gives a 2.8 ton reduction in payload; the Martin Marietta curve for shielding both stages gives a 2.7 ton reduction.[12] There is little disagreement about how to calculate payload reductions, although there still is some uncertainty as to whether those payload reduction should be taken in the form of RV or mission reductions.

The nominal calculations above are based on limited data on the efficacy of hardening large space structures to laser radiation. They assume that 2 g/cm^2 of ablator applied uniformly over the SS-18's 300 m^2 surface would protect it. At a typical ablation energy of 10 kJ/g, that thickness would give about 200 MJ/m^2, which is the value of hardening assumed in earlier studies.[13] Estimates based on textbook values of heats of vaporization can suggest specific hardnesses higher by about a factor of 2, but observed failures in tests at scale, which

involve a combination of ablation and rupture, result in a value a factor of 2 or more lower.

Thus, neither the attacker nor the defender has better than about a factor of 2 confidence in the ultimate value of various shielding materials, which impacts both about equally. That value will not be resolved until lasers of the required size are available to test structures, but a factor of 2 does not alter the evaluation that the penalties for hardening is a major effect.[14]

E. Special Cases

The literature also contains idealized discussions of shielding only the first stage, the second, the bus, or various combinations of them.[15] Comparisons of consistent configurations give results in agreement with those presented here, those by Martin Marietta, and those published earlier.[16] Shielding only the first stage essentially corresponds to the case inadvertently treated in the APS report, which is not acceptable in practice because it leaves the exposed upper stages relatively unhardened. Hardening only the second stage has also been discussed, but it cannot be justified either. Lasers can deliver lethal energies to the cloud tops, so leaving the first stage unhardened would gratuitously reduce the defensive requirements for boost phase effectiveness by about an order of magnitude, i.e., leave the requirements at about current levels.

Other types of missiles can be treated that have more stages, solid engines, higher accelerations, etc. More stages could decrease sensitivity to hardening mass slightly, but they would most likely be deployed with solid engines, whose lower exhaust velocities tend to increase sensitivity to hardening masses. Their net sensitivity could be greater than that of the SS-18 evaluated above. Such designs are, however, more dependent on engineering details than the SS-18s discussed above, so it is less useful to present purely theoretical analyses of their payload sensitivity.

F. Overall Comparisons

Uniformly hardening all stages requires about twice the payload penalties of the mass-weighted hardening used in the APS report, which essentially hardened only the first stage. Payload penalties for hardening all stages could amount to a significant fraction of the RVs carried for nominal hardnesses. The number of RVs removed could vary from 5 to 10, i.e., 50-199%, depending on the mission constraints accepted. If greater than nominal hardening was required, uniform protection of all stages could leave little useful payload with existing bus designs. These reductions are sufficiently great that the hardened missiles in nominal calculations should probably be viewed as carrying only 30-50% of the current number of RVs. While this analysis is stated in terms of space chemical lasers, it applies with minor modifications to space or ground based free electron or excimer lasers as well.

IV. SPINNING BOOSTERS

A related countermeasure that has an impact similar to retrofit hardening is spinning the booster around its vertical axis to continually bring more existing shielding material under the laser beam. Even for large amounts of hardening, laser kill times are on the order of a second or less.[17] Thus, for beams that can track the hot irradiated spot, the missile would have to rotate at least once per per second to have any impact, which does not appear to be a practical retrofit to existing missiles.[18]

Even for a non-tracking beam, the 3 m diameter SS-18 would have to rotate at over 20 rpm to significantly increase laser requirements. If the booster has radius r and rotates at angular velocity w and the laser spot has diameter d_S, material remains in the beam for a time $d_S/w \cdot r$. For that transit time to be less than the dwell time t_d the laser takes to deliver a lethal fluence, it is required that $w > d_S/r \cdot t$. For the SS-18's

$r = 1.5$ m, a beam with $d_s = 1$ m and a nominal $t = 0.3$ s gives $w > 2.2$ rad/s, i.e., over 20 rpm, which is difficult with liquid boosters. There are also accuracy issues, in that RVs released by PBVs rotating at such rates would miss their targets altogether. Retrofit hardening to those rates has not been studied; it is more difficult to retrofit additional tolerance to stress than to retrofit additional hardening, so hardening appears to be the preferred approach for the attacker.

V. OTHER COUNTERMEASURES

It has been observed that depressed trajectories "increase the time a missile spends within the atmosphere and is therefore unreachable by weapons for which the atmosphere is opaque."[19] That applies to some concepts; for lasers, however, which can reach essentially to the ground, the net effect of depressed trajectories is to increase the boost phase time during which the lasers can engage the missiles in proportion to their additional path length in the atmosphere. That is a factor of 2-3, which decreases the size of the defensive constellations needed by a like amount.[20]

VI. SCALING IMPACT OF COUNTERMEASURES

The discussion above treated the interaction of a single laser and missile. As missiles are hardened, laser constellations can be compacted to improve their performance and offset part of the hardening with reconfiguration. This section treats the overall offense-defense mass and cost tradeoffs when these constellation effects are included.

DEWs are characterized primarily by their brightness B, which is the product of their power P and mirror area A, divided by the square of their wavelength w, or[21]

$$B = PA/w^2. \qquad (1)$$

The 20 MW infrared chemical laser-10 m mirror, or "20-10" platforms often used for scaling estimates have brightnesses of

about 20 MW$\cdot\pi$(5 m/2.7 μm)$^2 \approx 2.2\cdot10^{20}$ W/sr. A platform of brightness B produces a flux of B/r^2 on targets at range r. That would destroy targets hardened to a fluence J in a dwell time

$$t = J/[B/r^2]. \quad (2)$$

For targets at r = 1,000 km hardened to a fluence of J = 200 MJ/m^2, that time is about 200 MJ/m^2 $\div$ [$2\cdot10^{20}$ W/Sr $\div$ $(10^6\text{m})^2$] $\approx$ 1 s. At shorter ranges t decreases as r^2. Thus, in a 100 s engagement, i.e., the simultaneous launch of very fast missiles, each laser could destroy about 100 missiles; so to negate the simultaneous launch of 1,000 fast missiles, about 10 lasers would have to be in range. The whole constellation would have to be 5-10 times larger, or 50-100 satellites in total, to account for the "absenteeism" of satellites that were elsewhere in their orbits at the time of launch.

Early estimates gave longer kill times, but did so on the unsupportable assumption that all engagements would take place at the maximum range possible, an error that affects kill times quadratically.[22,23] The APS report's estimate that the lasers would have to be 10 times larger resulted from its arbitrary assumption that a single laser had to engage all boosters.[24]

Refining those estimates requires proper averaging over the range between them and optimally allocating the lasers' fire. Several useful limiting solutions have been presented,[25] as has a near-exact, quasi-analytic solution that recovers them in the proper limits but produces constellations that are smaller by a factor of 2-4 for large constellations and bright platforms.[26] The analytic solution is relatively insensitive to engagement parameters, satellite altitudes, retarget times, and launch area.

Combined constellations scale as[27]

$$N = K(JM/BA_LT)^\Gamma, \quad (3)$$

where $\Gamma \approx$ 0.7-0.8 and $K = N/(JM/BA_LT)^\Gamma \approx 4\cdot10^{19}$ $(\text{m}^4/\text{sr})^\Gamma$ from the $\approx$ 50 chemical laser satellites of 20-10 performance needed for the "nominal" threat of M = 1,400 boosters hardened to

$J = 200\ MJ/m^2$ launched from an area of $A_L = 10\ (Mm)^2$ and vulnerable for $T = 100$ s.[28] For this report, the main concern is the constellation-hardness-missile scaling relationship, $N \propto (JM)^{\Gamma}$, which is the basis for constructing an overall mass or cost exchange ratio. The average cost exchange ratio is

$$CER = C_M \cdot M \div C_L N, \quad (4)$$

where C_M = \$ 100-200 M is the total cost of a survivable offensive missile,[29] and $C_L \approx$ \$ 400 M is the total cost of a laser platform.[30] For these values the average CER is about

$$CER = \$100\text{-}200M \cdot 1400\ msl \div \$\ 400\ M \cdot 50\ sat \approx 7\text{-}14{:}1, \quad (5)$$

which strongly favors the defense. Thus, for nominal parameters it would be ineffective for the attacker to attempt to proliferate missiles. For fixed J, CER $\propto M^{1-\Gamma}$, which increases for larger threats. The primary cost parameter, the marginal exchange ratio, is

$$CER' = (C_M/C_L)dM/dN \propto CER/\Gamma, \quad (6)$$

which increases about as rapidly with the threat. The question is how the CER varies with the hardness of the missiles. For fixed M, the scaling is given by Eq. (3) as

$$CER \propto N^{-1} \propto J^{-\Gamma}, \quad (7)$$

so that doubling the hardness would decrease the CER by $2^{-0.7} \approx 0.6$ to 4-8:1, which still favors the defense.

For retrofit hardening the shielding cannot be increased without decreasing the number of RVs carried, so the number of RVs per missile that is hardened varies as

$$m = m_o(1 - \sigma/\sigma_1), \quad (8)$$

where $m_o \approx 10$ is the number of RVs per missile without hardening, σ is the areal density of the missile's hardening, and σ_1 is the hardening at which the missile's payload falls to zero, which according to Fig. 1 is about 6-12 g/cm^2. The total number of RVs in the attack, mM, is thus

$$R = mM = m_o(1 - \sigma/\sigma_1)M, \quad (9)$$

so that to maintain a given number of attacking RVs, the attacker must increase the number of missiles launched as

$$M = R/m_o(1 - \sigma/\sigma_1) = M_o/(1 - \sigma/\sigma_1), \tag{10}$$

where M_o is the number in the absence of hardening. The missiles' hardness J also varies with σ as

$$J = J_o + j\cdot\sigma, \tag{11}$$

where J_o is the hardness in the absence of additional shielding, about 2 kJ/cm^2 for liquid boosters and perhaps 20 kJ/cm^2 for solids, and $j \approx 10$ kJ/g is the effective specific heat of the ablator. These values also roughly characterize the normal and hardened parameters for buses. Substituting Eqs. (10)-(11) and N from Eq. (3) into Eq. (4) gives

$$CER = C_M\cdot[M_o/(1 - \sigma/\sigma_o)]^{1-\Gamma} \div C_L K[(J_o+j\cdot\sigma)/BA_L T]^{\Gamma} \tag{12}$$

as the laser constellation's average cost-effectiveness ratio against hardened missiles.

Figure 2 shows the variation of the CER with σ for liquids. For no retrofit hardening the advantage approaches 40; for large σ it drops to 3-5. The top curve is for the nominal ablator specific heat of j = 10 kJ/g; the lower curve is for 20 kJ/g. For large σ they are separated by about a factor of $2^{0.75} \approx 1.7$ as expected from Eq. (12). For the former, at σ = 20 MJ/kg the lasers' advantage is about a factor of 7, as calculated previously for the the corresponding 6 ton shielding directly above on Fig. 1. For 40 MJ/m^2, i.e., 4 cm of ablator, the CER drops to about 5. Thus, the hardening penalties plus the reconfiguration of the constellation permit the lasers to maintain roughly a 3- to 5-fold advantage. The curves are drawn for a cost ratio of C_M/C_L = \$ 100 M/400 M, scaling linearly to other values.

Figure 3 shows the corresponding curves for solids. The main difference is that solid rocket cases have significant intrinsic hardness, which largely eliminates the lasers' strong advantage against liquids at $\sigma \approx 0$. For large σ, the curves for solids are essentially those for liquids, translated by the 20 kJ/cm^2 intrinsic hardening of the solids' cases.

Figure 4 shows the constellation sizes. The upper curve is for solids, which is translated upward by about a factor of 1.7 from the liquid curve for reasons noted above. For small σ, the constellations for liquid boosters are much smaller than those for solids, but by 20-40 kg/m^2 the difference is no longer large. For large shielding the constellation size varies as $N \alpha J^{\Gamma} \alpha \sigma^{\Gamma}$ in accordance with Eqs. (3) and (11). The constellations become large, but remain well below those of the offense, so they remain cost effective relative to offensive proliferation to the defense according to Figs. 2-3.

Figures 2-3 are shown for large lasers and short engagements, i.e., 20-10 platforms, T = 100 s, and A_L = 10 Mm^2. By Eq. (12) the parameters of the defense enter as the product BA_LT, which is a useful scaling over a wide range of parameters. The area scaling is, however, better represented by $N \alpha f(A_L)$, where f empirically has the values $f(10\ Mm^2) = 1$, $f(1\ Mm^2) = 0.5$, and $f(0.1\ Mm^2) \approx 0.25$.[31] Thus, N scales very weakly on A_L. In going from the near term through the mid term to the long term--roughly the next three successive decades--B increases as about 1, 4, and 16, and T decreases as 1, 1/2, and 1/5. Combining these variations with the area variation of $f(A_L)$ indicates that the product of the key defensive parameters remains about constant, so the scaling relationships discussed above and the parameters used in the figures should remain roughly valid throughout the near to long term transition. Thus, in the whole hardening analysis the only significant variations are that of CER on σ, as shown in Figs. 1-4, and on B^{Γ} for higher brightnesses, as shown in Eq. (13). The latter scaling and the flexibility of the defense to increase B above the nominal 20-10 level gives the defense the option to offset any reductions in platform size by increasing platform brightness. The cost to do so should increase much less than the brightness.

VII. SUMMARY AND CONCLUSIONS

The primary retrofit countermeasures to laser defenses are hardening and spinning the offensive missiles. Spinning could be useful, but would require rates higher than those that have been studied and which could be hard to retrofit. Earlier OTA and UCS studies treated the impact of hardening on the laser requirements but ignored the impact of hardening penalties on the missiles themselves. The APS report treated the missile hardening penalties, but hardened the missiles' stages unevenly, which resulted in factor of 2 underestimates of the overall payload penalties. The APS corrected predictions could amount to a significant fraction of the payload of current missiles.

The only significant variable is the thickness of the hardening applied. The defense's cost effectiveness is degraded, but not eliminated, by extremely thick ablators. There are residual factor of 2 uncertainties in the amount of hardening to be used and its overall effectiveness, but they do not offset the advantage the defense enjoys for nominal conditions. Cost-effectiveness ratios favor the defense both with and without hardening. Thus, retrofit hardening appears to be a possible, but not a pivotal, countermeasure.

APPENDIX A. HARDENING PENALTIES

For uniform stage hardening, the masses required to optimally shield a two stage missile are[32]

$$E^2 = [(X+P)/(X+P-M_{P1})][(Y+P)/(Y+P-M_{P2})], \tag{A1}$$

where the bus payload P includes the bus hardening. The quantities in Eq. (1) are

$$X = (1+f)(M_{P1}+M_{P2}) + M_{A1} + M_{A2}, \tag{A2}$$

$$Y = (1+f)M_{P2} + M_{A2}, \tag{A3}$$

where f is the ratio of structural material to propellant,

$$E^2 = \exp(V/c), \tag{A4}$$

is the ideal stage ratio, and M_{XN} is the propellant (ablator) mass for X = P (A) of the first [second] stage for N = 1 [2]. The total payload is

$$P = [-b + (b^2-4ac)^{1/2}]/2a, \tag{A5}$$

where

$$a = E^2 - 1, \tag{A6}$$

$$b = (E^2 - 1)(X + Y) - E^2(M_{P1} + M_{P2}), \tag{A7}$$

$$c = (X - M_{P1})(Y - M_{P2}) - XY. \tag{A8}$$

Figure 1 uses the V = 7 km/s, c = 3.06 km/s, f = 0.15, M_{P1} = 146.2, and M_{P2} = 30.4 tons of the APS report. The upper curve takes the first, second, and bus hardening masses to be 62.5, 25, and 12.5% of the total hardening mass; i.e., it assumes that the hardening masses for each stage are proportional to their areas.

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32. APS Report, op. cit., Eq. (2.10).

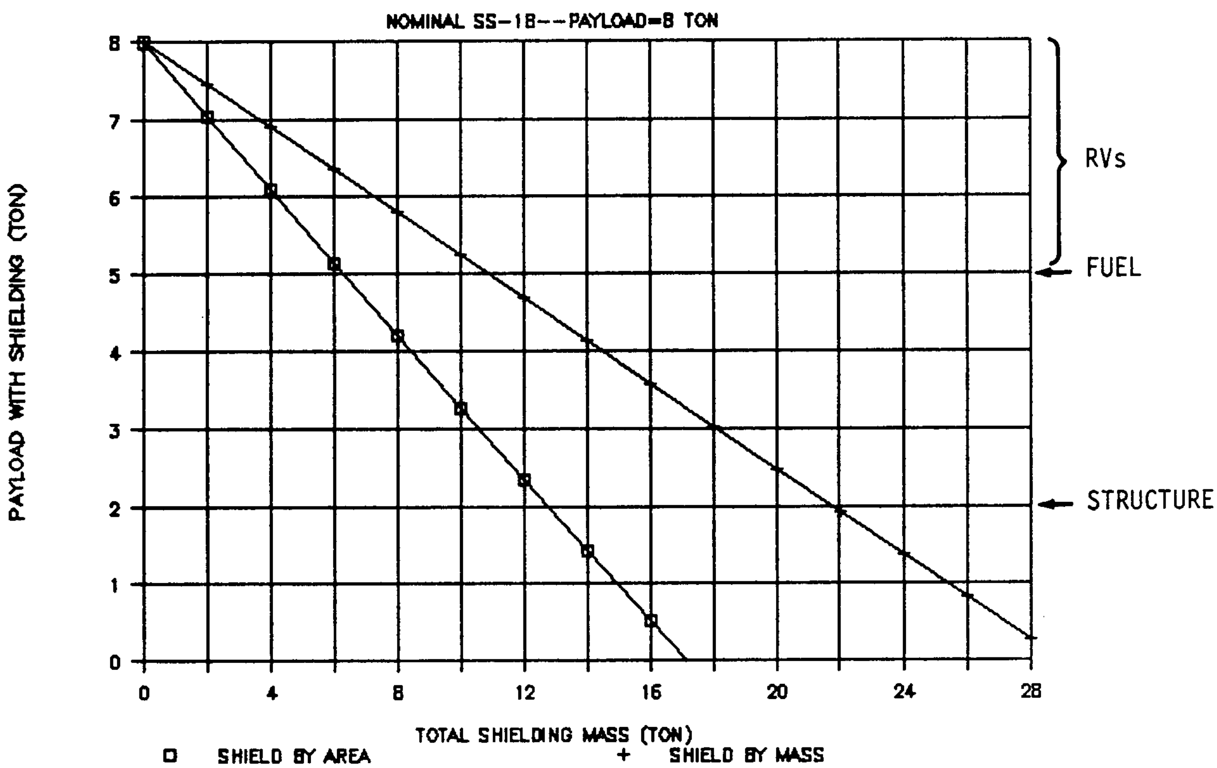

Fig. 1. Payload penalties for shielding large liquid missiles against lasers, estimated for nominal SS-18 missiles and limiting ablator material performance. Top curve is for shielding proportional to mass; lower curve is for shielding proportional to area.

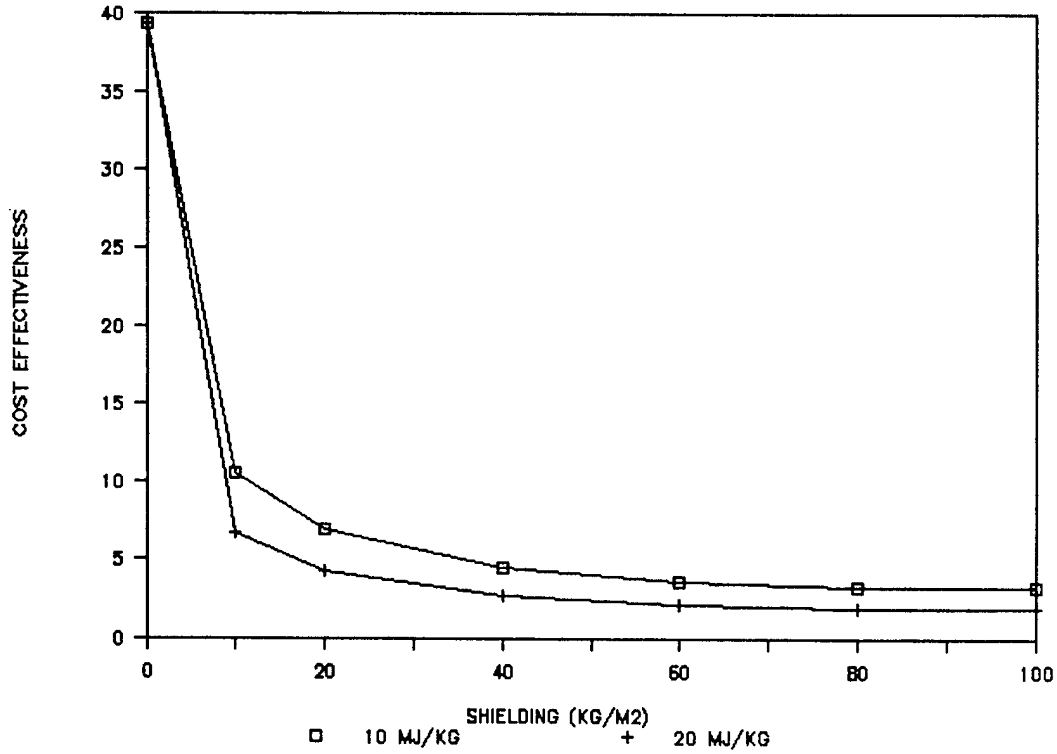

Fig. 2. Cost effectiveness of hardening large liquid missiles against laser constellations.

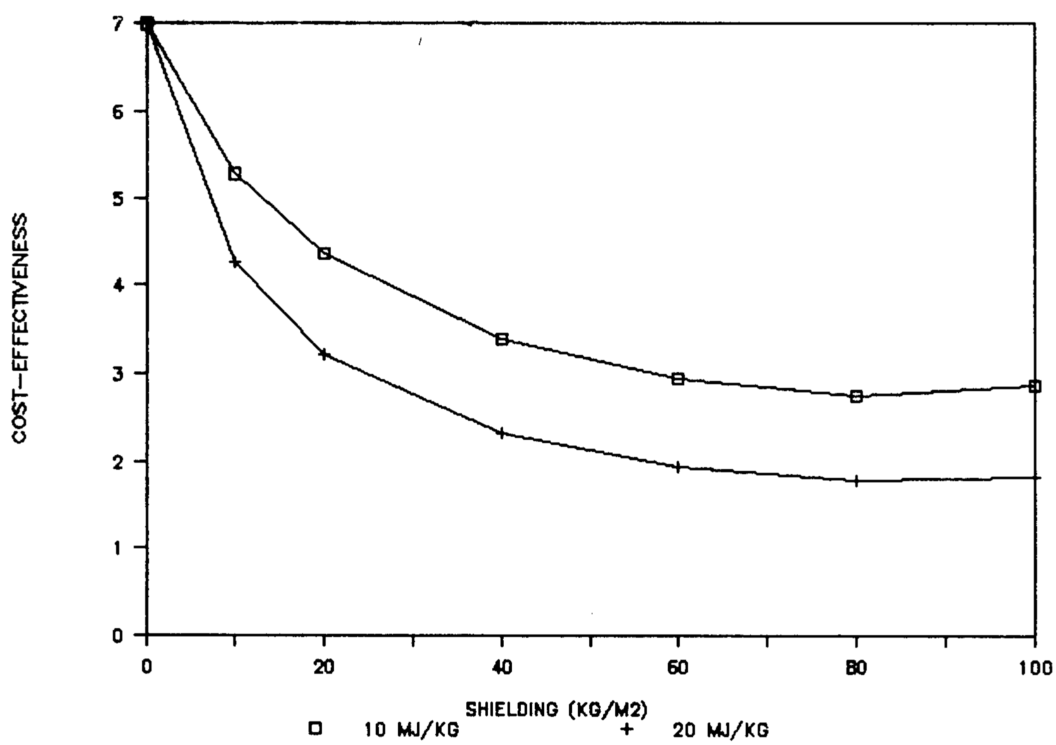

Fig. 3. Cost-effectiveness ratio for hardening solid missiles against laser constellations.

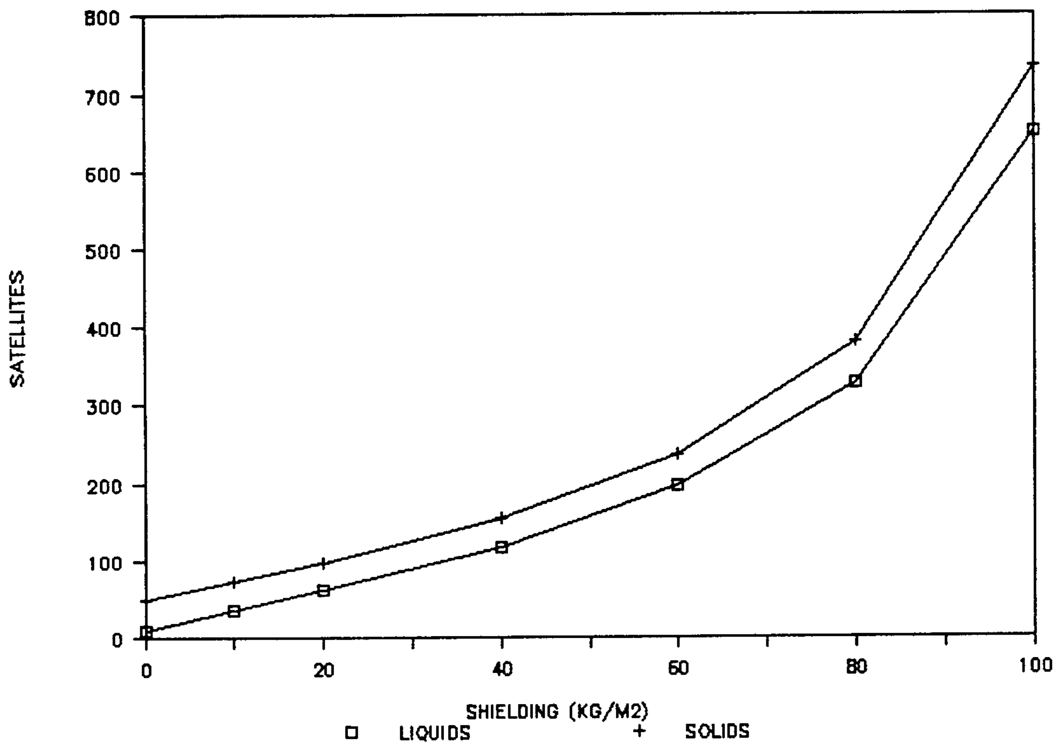

Fig. 4. Laser constellation size vs shielding of large siquid and solid missiles.

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